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Effects of Ion Collisions on Quasilinear Heating by the Current-Driven Ion Cyclotron Instability in the High Latitude Ionosphere

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Using an effective relaxation time model, the effects of ion-ion and ion-neutral collisions on quasilinear ion heating by the current-driven ion cyclotron instability in the high latitude ionosphere have been studied. For conditions typical of the high latitude lower (200-300 km) F-region ionosphere, it is found that the combined effects of ion-neutral and ion-ion collisions tend to isotropize $(T_\perp/T_\| \simeq 1)$ the perpendicular $(T_\perp)$ and parallel $(T_\|)$ ion temperatures on time scales on the order of several tens to hundreds of NO^+ cyclotron periods for wave amplitudes $e\phi/T_e = 0.2$. Here, ϕ is the wave electrostatic potential, T_e the electron temperature (in energy units), e is the electron charge. In addition, for the high latitude upper (600 km) F-region ionosphere it is found that stronger anisotropy $(T_\perp/T_\| > 3)$ can be sustained even in the presence of ion collisions with waves with amplitudes

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19. ABSTRACTS (Continued)

$e\phi/T_e$ = 0.2. For larger amplitude waves $e\phi/T_e$ = 0.4, we find that the heating is weakly anisotropic at low altitudes (200-300 km) and strongly anisotropic at higher (600 km) altitudes. In both wave amplitude regimes (0.2 and 0.4), we find perpendicular ion heating factors ~ 2-10 for altitudes in the range 300-600 km, with the larger perpendicular heating occurring at higher altitudes and larger wave amplitudes. ~~We compare our~~ results with recent rocket and satellite observations in the high latitude ionosphere.

Ion cyclotron instability.

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CONTENTS

EFFECTS OF ION COLLISIONS ON QUASILINEAR HEATING BY THE CURRENT-DRIVEN ION CYCLOTRON INSTABILITY IN THE HIGH LATITUDE IONOSPHERE

I. INTRODUCTION

Recently, much interest has been devoted to the role of the high latitude ionosphere in influencing magnetospheric dynamics and morphology. In particular, the problem of the high latitude ionosphere as a source of magnetospheric plasma has come under intense study in the last few years. Several investigators have observed upward flowing accelerated ionospheric ions in the auroral zone space plasma [Shelley et al., 1976; Sharp et al., 1977; Mizera and Fennel, 1977; Ghielmetti et al., 1978; Croley et al., 1978; Whalen et al., 1978; Klumpar, 1979; Collin et al., 1981; Gorney et al., 1981; Yau et al., 1983; Moore et al., 1986]. The particle distributions of these upflowing ions can be characterized as either beam-like with pitch angles near 180 degrees or conical with pitch angles between 90 and approximately 130 degrees. Gorney et al. [1981] have concluded that the beam-like distributions are most often observed above 4000-5000 km. Conic distributions, on the other hand, have been observed near 1500 km [Klumpar, 1979; Ungstrup et al., 1979] and at rocket altitudes near 400-600 km [Whalen et al., 1978; Yau et al., 1983, Basu et al., 1988] suggesting a low altitude generation region for ion conics. Furthermore, Gorney et al. [1981] have shown that the large majority of conic distributions have energies below a few hundred eV implying a significant ionospheric component. Moore et al. [1986] have recently observed perpendicular ion heating at high (700 km) and low (300-350 km) altitudes with the TOPAZ sounding rockets. Their observations show that ion heating at 700 km is correlated with the lower-hybrid wave activity while ion heating observations at 300 km is correlated with keV electron precipitation. They do not observe any significant ion heating below 270 km.

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Kintner et al. [1978], using S3-3 satellite data, have measured electrostatic ion cyclotron waves near regions of upward flowing ions. At lower altitudes (400-600 km) Yau et al. [1983] have observed ion cyclotron wave activity near ion transverse acceleration regions. Bering [1984] has given evidence of ion cyclotron wave activity also at low altitudes (350 km) in the diffuse aurora. Recently, Basu et al. [1988] have observed apparent ion conics at approximately 350 km in the presence of wave activity in the ion cyclotron range of frequencies and large field aligned currents. In addition to low altitude ion heating in the ionosphere, intense local heating has been observed at much higher altitudes in the magnetosphere where the plasma is collisionless. Recent papers have also proposed that ion heating could occur cumulatively over several thousand kms [Temerin, 1986; Retterer et al., 1987; Andre et al., 1988].

The ion conic distributions have been interpreted as resulting from perpendicular heating of ions at low altitudes followed by parallel upward adiabatic motion due to the *magnetic mirror force* [Sharp et al., 1977]. Proposed perpendicular heating mechanisms include collisionless electrostatic ion cyclotron waves [Ungstrup, 1979; Okuda and Ashour-Abdalla, 1981], lower hybrid waves [Chang and Coppi, 1981], and electrostatic shocks and/or oblique double layers [Mozer et al., 1980; Yang and Kan, 1983]. Recently, Satyanarayana et al. [1985] have discussed the linear theory of the electrostatic ion cyclotron instability in the high latitude ionosphere where collisional effects are important. They have shown that electron collisions are destabilizing, under realistic ionospheric conditions, and lead to the excitation of the collisional ion cyclotron instability [D'Angelo, 1973; Chaturvedi and Kaw, 1975; Chaturvedi, 1976; Suszcynsky et al., 1986] in the bottomside ionosphere. Ion collisions were found to have a stabilizing influence on the

collisional ion cyclotron instability. Dupree's resonance broadening theory was used by Satyanarayana et al. [1985] to estimate the nonlinear saturated amplitudes of the collisional ion cyclotron instability in the high latitude ionosphere. Furthermore, Satyanarayana et al. [1985] conjectured that the collisional ion cyclotron instability should be a source of transversely accelerated heavy ions at higher altitudes as observed in several studies [Hoffman et al., 1974; Hultqvist, 1983; Craven et al., 1985].

However, Satyanarayana et al. [1985] did not discuss the ion heating by ion cyclotron waves in regions of the collisional high latitude ionosphere nor did they discuss the regions of the high latitude ionosphere where ion conic formation might be possible. In this brief report we study the effects of ion-ion and ion-neutral collisions such as isotropization and cooling on quasilinear ion heating by the current-driven ion cyclotron instability in the high latitude ionosphere. We model the heating with collisionless quasilinear heating rates to determine the threshold altitude for conic observations in the bottomside ionosphere. In Section 2 we give the basic collisional model used for the ions in this study. In Section 3 we discuss approximate quasilinear heating rates with collisional effects. Finally, in Section 4 we summarize and discuss our results.

II. MODEL

We consider a homogeneous collisional plasma in a uniform magnetic field $\underline{B}$ along the z-direction, i.e., $\underline{B} = B_o\hat{z}$. In this study, we use local theory and ignore inhomogeneous effects, e.g., density and temperature gradients. As a result, we assume $k_\perp L_\perp \gg 1$ and $k_\parallel L_\parallel \gg 1$ where $L_\perp$ and $L_\parallel = L_z$ are the gradient scale lengths of temperature and/or density in the direction perpendicular and parallel to the magnetic field, respectively, and $k_\perp$ and $k_\parallel = k_z$ are the perpendicular and parallel components of the

instability wavevector $\underline{k}$. We consider the altitude range of approximately 200-600 km in the high latitude auroral and polar ionosphere. In this altitude regime electron and ion collisional effects are important [Satyanarayana et al., 1985] for the evolution of the current-driven ion cyclotron instability. The electrons are treated in the collisionless limit in this study. We consider only ion-ion and ion-neutral collisions since for $200 \lesssim z \lesssim 1000$ km ν_{in}, $\nu_{ii} > \nu_{ie}$ since $\nu_{ii} \approx (m_i/m_e)^{1/2} \nu_{ie}$, [Spitzer, 1962; Trubnikov, 1965], where ν_{ii} is the ion-ion collision frequency, ν_{in} the ion-neutral collisional frequency, ν_{ie} the ion-electron collision frequency, m_i the ion mass and m_e the electron mass.

The basic equation describing the evolution of the plasma distribution function f_α of the current-driven electrostatic ion cyclotron instability in a collisional plasma can be written as

$$\frac{\partial f_\alpha}{\partial t} + \underline{v}_\alpha \cdot \nabla f_\alpha + \frac{e_\alpha}{m_\alpha}\left(\underline{E} + \frac{1}{c}\underline{v}_\alpha \times \underline{B}\right) \cdot \nabla_{\underline{v}_\alpha} f_\alpha = \left(\frac{\partial f_\alpha}{\partial t}\right)_c \qquad (1)$$

where α denotes species i or e, e_α the charge of species α, m_α the mass of species α, $\underline{E}$ is the electric field, $\underline{B}$ is the magnetic field, c the speed of light, $\nabla_{\underline{v}_\alpha} \equiv \partial/\partial \underline{v}_\alpha$, $\nabla = \partial/\partial \underline{x}$, and $(\partial f_\alpha/\partial t)_c$ is the contribution due to collisional effects. Satyanarayana et al. [1985] has given a complete discussion of the linear theory of the current-driven electrostatic ion cyclotron instability, using Eq. (1), with $(\partial f_\alpha/\partial t)_c$ given by a BGK collision operator both for electrons and ions. In this study we take a Fokker-Planck representation [Montgomery and Tidman, 1964] of $(\partial f_\alpha/\partial t)_c$ for ion-ion Coulomb collisional effects. This representation can be approximated by using an effective relaxation time model [Trubnikov, 1965]. For ion-neutral collisions we adopt the approach outlined in Satyanarayana et al. [1985].

III. QUASILINEAR ION HEATING WITH COLLISIONAL COOLING

We take the ion distribution function to be a bi-Maxwellian with effective temperatures $T_\perp$ and $T_\parallel \equiv T_z$ in the direction perpendicular and parallel to the magnetic field:

$$f_i\left(v_\perp, v_\parallel\right) = \left(\frac{m_i}{2\pi T_\perp}\right)\left(\frac{m_i}{2\pi T_\parallel}\right)^{1/2} \exp\left[-\frac{v_\perp^2}{2(T_\perp/m_i)} - \frac{v_\parallel^2}{2(T_\parallel/m_i)}\right]$$

In lieu of an exact treatment of quasi-linear ion heating including ion-ion collisions, as implied by (1), we make an approximation. In the limit of weak collisions we set the right hand side of (1) to zero and solve for the quasi-linear ion heating rates without ion collisional effects (first term on right hand side of (2) and (3) below) as has been derived by others [Davidson, 1972; Dakin et al., 1976., Ashour-Abdalla and Thorne, 1978, Okuda and Ashour-Abdalla, 1981]. In the next order we neglect the wave effects and solve (1) for the effects of ion collisions. The principal ion-ion collisional effect gives a temperature isotropization term proportional to $(T_\perp - T_\parallel)$ using an effective relaxation time model [Trubnikov, 1965] (second term on right hand side of (2) and (3)). The quasilinear heating rates with ion-ion collisions in a single species plasma can then be written:

$$\frac{dT_\perp}{dt} = \left\{\frac{e^2\Omega_i^2}{T_\perp}\left(\frac{m_i}{2\pi T_\parallel}\right)^{1/2} \sum_n \sum_{\underline{k}} \frac{n^2|\phi_k|^2\Gamma_n(s)}{k_\parallel}\right.$$

$$\left. \times \exp\left[-\frac{m_i(\omega_k - n\Omega_i)^2}{2k_\parallel^2 T_\parallel}\right]\right\} - \nu_{eff}\left(T_\perp, T_\parallel\right)\left(T_\perp - T_\parallel\right) \qquad (2)$$

$$\frac{dT_{\parallel}}{dt} = \left\{\frac{e^2}{T_\perp} \Omega_i \left(\frac{m_i}{2\pi T_{\parallel}}\right)^{1/2} \sum_n \sum_{\underline{k}} \frac{n(\omega - n\Omega_i)\Gamma_n(s)|\phi_{\underline{k}}|^2}{k_{\parallel}}\right.$$

$$\left. \times \exp\left[-\frac{m_i(\omega_k - n\Omega_i)^2}{2k_{\parallel}^2 T_{\parallel}}\right]\right\} + 2\nu_{eff}(T_\perp, T_{\parallel})(T_\perp - T_{\parallel}) \qquad (3)$$

where $\Omega_i = eB_0/m_i c$, $\underline{E} = -\nabla\phi$, $\Gamma_n(s) = I_n(s)\exp(-s)$, $s = k_\perp^2\rho_i^2$, I_n the modified Bessel function of order n, ω_k is the linear frequency, $\phi_{\underline{k}}$ is the Fourier transform of the electrostatic potential ϕ such that $e\phi_k/T_e$ is dimensionless, $\nu_{eff} = 2\pi^{1/2}e^4 n_i\lambda m_i^{-1/2}(T_{\parallel})^{-3/2}A^{-2}[(A + 3)(\tan^{-1}A^{1/2})/A^{1/2} - 3]\sec^{-1}$, $\lambda = 23 - \ln[(n/T^3)^{1/2}]$ is the Coulomb logarithm and $A = (T_\perp - T_{\parallel})/T_{\parallel} > 0$. We note that for $\nu_{eff} = 0$ the quasilinear heating rates reduce to those given in Eq. (5) and (6) in Okuda and Ashour-Abdalla [1981]. Equations (2) and (3) describe the evolution of $T_\perp(t)$ and $T_{\parallel}(t)$ with quasilinear heating as a source and ion collisional cooling as a sink. (Eq. (2) and (3) include only the effects of ion-ion collisions in the form of ν_{eff}. In Eq. (6) and (7) we generalize the model and add a second ion species and ion-neutral collisions as well.) The approximate quasi-steady state ion temperatures $T_\perp$ and $T_{\parallel}$ and anisotropy $(T_\perp - T_{\parallel})$ can be found by balancing the source and sink. An analysis similar to ours has been performed by Ionson et al. (1976) who considered collisional effects on ion cyclotron wave heating at altitudes greater than 2000 km in the auroral zone. However, they did not compute a minimum altitude below which ion cyclotron wave heating would be isotropized by collisions nor did they use quasilinear effects as an ion heating source.

Equations (2) and (3) are difficult to solve exactly since the spectrum $|\phi_{\underline{k}}|^2$ of the current-driven ion cyclotron instability is not well known.

Numerical simulations [Okuda and Ashour-Abdalla, 1981] indicate that $|\phi_{\underline{k}}|^2$ peaked about $\underline{k}$ corresponding to the fastest-growing fundamental $\omega \simeq \Omega_i$ harmonic mode. Equations (2) and (3) can be written, approximately,

$$\frac{\partial T_\perp}{\partial t} \simeq \left\{ \left(\frac{e\phi_{\underline{k}_m}}{T_e}\right)^2 \frac{T_e^2}{T_\perp}\Omega_1^2 \frac{\Gamma_1(s)}{k_\parallel}\left(\frac{m_i}{2\pi T_\parallel}\right)^{1/2} \exp\left[\frac{-m_i(\omega_{\underline{k}_m} - \Omega_i)^2}{2k_\parallel^2 T_\parallel}\right]\right\}$$

$$- \nu_{eff}(T_\perp, T_\parallel)(T_\perp - T_\parallel) \tag{4}$$

$$\frac{\partial T_\parallel}{\partial t} \simeq \left\{ \left(\frac{e\phi_{\underline{k}_m}}{T_e}\right)^2 \frac{T_e^2}{T_\perp}\Omega_i \left(\omega_{\underline{k}_m} - \Omega_i\right) \frac{\Gamma_1(s)}{k_\parallel} \left(\frac{m_i}{2\pi T_\parallel}\right)^{1/2} \exp\left[\frac{-m_i(\omega_{\underline{k}_m} - \Omega_i)^2}{2k_\parallel^2 T_\parallel}\right]\right\}$$

$$+ 2\nu_{eff}(T_\perp, T_\parallel)(T_\perp - T_\parallel) \tag{5}$$

where $\underline{k}_m$ corresponds to the instability wavevector $\underline{k}$ giving maximum linear growth for the kinetic collisionless ion-cyclotron instability. In order to model a more realistic ionosphere, we generalize (4) and (5) by adding a second minor species and ion-neutral collisions [Satyanarayana et al., 1985]. The ion-neutral collisions help model the eventual wave energy transfer to neutrals. We model the multispecies collisional effects with a collision frequency ν_m [Banks and Kockarts, 1973] and ion-neutral collisions with the collision frequency ν_{in}. In a multicomponent plasma, e.g., NO^+ and O^+, Eq. (4) and (5) become

$$\frac{\partial T_\perp}{\partial t} = Q(T_\perp, T_\parallel)\Omega_i - \nu_{eff}(T_\perp, T_\parallel)(T_\perp - T_\parallel) - \nu_m(T_\perp - T_m) - \nu_{in}(T_\perp - T_n) \tag{6}$$

$$\frac{\partial T_{\parallel}}{\partial t} = Q(T_{\perp},T_{\parallel})(\omega_{\underline{k}_m} - \Omega_i) + 2\nu_{eff}(T_{\perp},T_{\parallel})(T_{\perp}-T_{\parallel}) - \nu_m(T_{\parallel}-T_m) - \nu_{in}(T_{\parallel}-T_n) \qquad (7)$$

where

$$Q(T_{\perp}, T_{\parallel}) = \left(e\phi_{\underline{k}_m}/T_e\right)^2 (T_e/T_{\perp})\Gamma_1(s)\left[\Omega_i(m_i/2\pi T_{\parallel})^{1/2}/k_{\parallel}\right]\exp\left[\frac{-m_i(\omega-\Omega_i)^2}{2k_{\parallel}^2 T_{\parallel}}\right]$$

$$\nu_m = 1.8 \times 10^{-19} \frac{(m_{NO^+}\, m_{O^+})^{1/2}\, n_{O^+}\, \lambda_{NO^+O^+}}{\left(m_{NO^+}T_{O^+} + m_{O^+}T_{NO^+}\right)^{3/2}} \sec^{-1}$$

$$\nu_{in} = 6 \times 10^{-21}\, n_n(T_i/m_i)^{1/2}\sec^{-1}$$

Ω_i is the ion cyclotron frequency of the majority ions, n_n is the neutral density, T_m is the temperature of minority ions (T_{NO^+},T_{O^+} or T_{H^+}) assumed to be in equilibrium with the electrons ($T_m \sim T_e$), λ is the Coulomb logarithm, T_n the neutral temperature, $T_{\perp}$ and $T_{\parallel}$ refer to the temperature perpendicular and parallel to the geomagnetic field of the majority ion species, with all other symbols retaining their standard meaning.

In the following, we fix ($e\phi_{\underline{k}_m}/T_e$), $k_{\parallel}/k_{\perp}$ and solve (6) and (7) for $T_{\perp}(t)$, $T_{\parallel}(t)$. For simplicity of notation, in the following we drop the subscript $\underline{k}_m$. We estimate typical values for $e\phi/T_e$. From Yau et al [1983] and Bering [1984] we use typical electric fields E = 10-40 mV/m in regions of ion energization and find $e\phi/T_e \simeq eE/k_mT_e \simeq 0.2 - 0.4$ for $T_e \simeq 3000°K$ and $k_m \simeq \rho_i^{-1}$ with $\rho_i \simeq 2.5$m the approximate O^+ ion gyroradius in the high latitude ionosphere. This range of values of $e\phi/T_e$ is also consistent with computer simulations [Okuda and Ashour-Abdalla, 1981; Pritchett et al., 1981] of the current driven electrostatic ion cyclotron instability and S3-3 satellite observations at high altitudes [Mozer et al., 1980; Kintner et al. 1979]. The quantity ($\omega - \Omega_i$) is taken to be ~ $\Gamma_1\ \Omega_i$ from the linear

dispersion relation of current driven ion cyclotron waves (Satyanarayana, et al., 1985). We set $k_{\parallel} = 0.1\ k_{\perp}$ since this value of $k_{\parallel}$ gives maximum linear growth [Satyanarayana et al., 1985]. In addition we normalize $T_{\perp}$, $T_{\parallel}$ with respect to T_e and the time t is normalized by Ω_i where Ω_i is the ion gyrofrequency of the majority ion.

Fig. 1 gives the evolution of $T_{\perp}$ and $T_{\parallel}$ according to Eq. (6) and (7) as a function of time at several different altitudes in the high latitude ionosphere given in Table 1 [Banks and Kockarts, 1973, Schunk et al., 1975, 1976]. In Fig. 1 we fix $e\phi/T_e = 0.2$. Curves A, B, C, and D correspond to altitudes 200, 300, 400, and 600 km, respectively. In general, we find increasing anisotropy with altitude with $T_{\perp}/T_{\parallel} \approx 1.4$ at low altitudes (curve A, 200 km) and $T_{\perp}/T_{\parallel} \approx 3.1$ at higher altitudes (curve D, 600 km) for several hundred ion cyclotron periods.

Fig. 2 displays the evolution of $T_{\perp}(t)$ and $T_{\parallel}(t)$ at the same altitudes as Fig. 1 but with a larger ion cyclotron wave amplitude $e\phi/T_e = 0.4$. Curves A, B, C, and D correspond to the same altitudes as in Fig. 1. From Fig. 2 we find increased heating compared to the smaller wave amplitude case in Fig. 1. We also note increasing anisotropy with altitude with $T_{\perp}/T_{\parallel} \approx 1.9$ at low altitudes (curve A, 200 km) and $T_{\perp}/T_{\parallel} \approx 6.4$ at higher altitudes (curve D, 600 km) again on the time scale of several hundred ion cyclotron periods. The evolution of $T_{\perp}(t)$ and $T_{\parallel}(t)$ using variations of the model ionospheric parameters contained in Table 1 was also studied with the results qualitatively similar to those displayed in Figs. 1-2.

The threshold altitudes above which we find strong anisotropic heating are near or just below the F-region peak in the high latitude ionosphere for wave amplitudes $e\phi/T_e = 0.2, 0.4$, respectively. We note that both the ion-neutral and ion-ion collisions contribute to the isotropization below the F-region peak. Since heavy ions such as $NO^+(O_2^+)$ or O^+ are major

species at these altitudes, we conjecture that heating by large amplitude collisional EIC may cause heavy ion conic distribution above the F region.

IV. SUMMARY AND CONCLUSIONS

Using an effective relaxation time model, we have made a preliminary study of the effects of ion-ion and ion-neutral collisions on quasilinear ion heating due to the current-driven ion cyclotron instability in the high latitude ionosphere. For conditions typical of the upper altitude high latitude F-region ionosphere (600 km) we find that strong temperature anisotropies $T_{\perp}/T_{\parallel} > 3$ for O^+ can be sustained even in the presence of ion collisional effects for several hundred O^+ ion cyclotron periods for ion cyclotron wave amplitudes $e\phi/T_e = 0.2$ and 0.4 as predicted by quasilinear theory. For the lower altitude F-region ionosphere (200-300 km) we find approximate collisional isotropization $T_{\perp}/T_{\parallel} \approx 1$ for wave amplitudes $e\phi/T_e = 0.2$ on time scales of a few tens to hundreds of NO^+ ion cyclotron periods. For larger wave amplitudes $e\phi/T_e = 0.4$ we find only weakly anisotropic heating at lower F-region altitudes (200-300 km). We conclude that ion conics driven by the electrostatic ion cyclotron instability will be seen at altitudes greater than approximately 300-400 km in the high latitude ionosphere. This finding is consistent with recent data derived from rocket experiments [Moore et al., 1986] which indicate significant ion perpendicular heating at altitudes above 250-300 km in the high latitude ionosphere. Our results are also consistent with recent DE satellite observations of Basu et al. [1988] who measure conic formations only for densities $n_e \lesssim 2 \times 10^5$ cm^{-3} in the presence of large field-aligned currents and ion cyclotron wave activity. In addition, it should be pointed out that Figs. 1 and 2 show perpendicular ion heating, even in those cases where near isotropy occurs. It is clear from Figs. 1 and 2 that curves B-D

(altitudes from 300-600 km) show perpendicular ion heating factors from 2-10 depending on altitude and EIC wave amplitudes (larger perpendicular heating occurring at higher altitudes and larger wave amplitudes). For Fig. 2 ($e\phi/T_e = 0.4$) even curve A (altitude of 200 km) shows a perpendicular ion heating factor ~2. Consequently, if we assume the quasilinear heating rate to apply for the collisional EIC, collisional ion cyclotron waves could provide a means for a low altitude pre-acceleration (or heating) region.

In this study we have used an essentially empirical model, the effective relaxation time model, to study the effects of ion collisions on quasi-linear heating by the current-driven ion cyclotron instability in the high latitude near earth space plasma environment. Our aim was to develop a simple model of time scales for ion collisional relaxation in the high latitude ionospheric environment and to balance these relaxation times with those associated with wave heating in order to better characterize possible ion conic generation and formation. In order to gain more complete information about the ion distribution function, collision models that are both more realistic and sophisticated will have to be employed. We defer such studies to future work.

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Table 1

Curve	Altitude(km)	$n_{NO^+}(cm^{-3})$	$n_{O^+}(cm^{-3})$	$n_n(cm^{-3})$
A	200	1×10^5	1.5×10^4	7.5×10^9
B	300	2.1×10^4	1×10^5	7.5×10^8
C	400	2.5×10^3	7×10^4	1.2×10^8
D	600	1×10^2	2.8×10^4	5.6×10^6

Note: $n_e = n_{NO^+} + n_{O^+}$

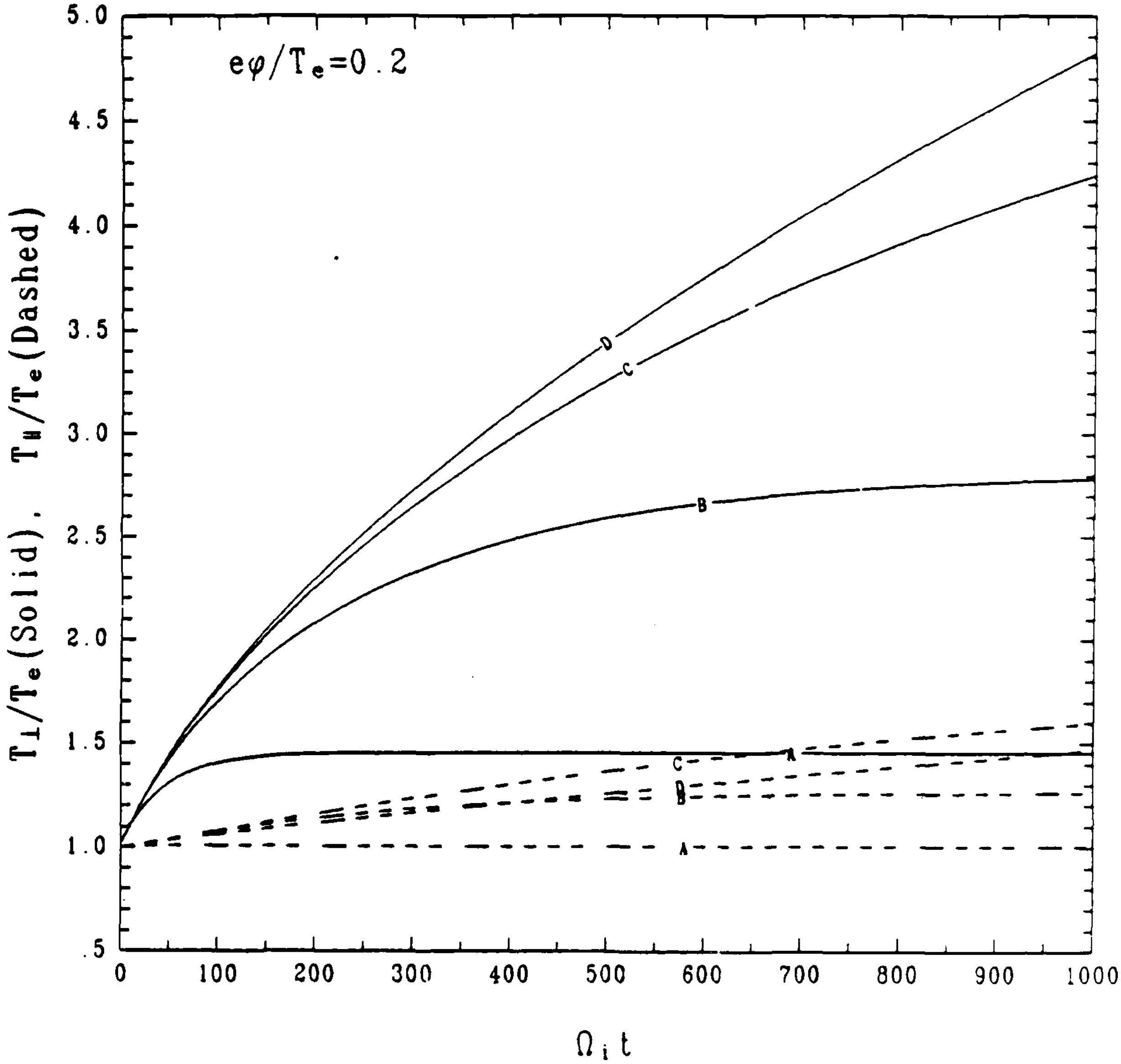

Fig. 1. Plot of $T_\perp(t)$ (solid lines) and $T_{||}(t)$ (dotted lines), both in units of electron temperature (T_e), as a function of time, in units of ion cyclotron frequency, of the majority ions from numerical solution of Eq. (6) and (7) for parameters indicated in Table 1 with $e\phi_{k_m}/T_e$ = 0.2. Curves A, B, C, and D represent altitudes 200 km, 300 km, 4^^ km, and 600 km respectively.

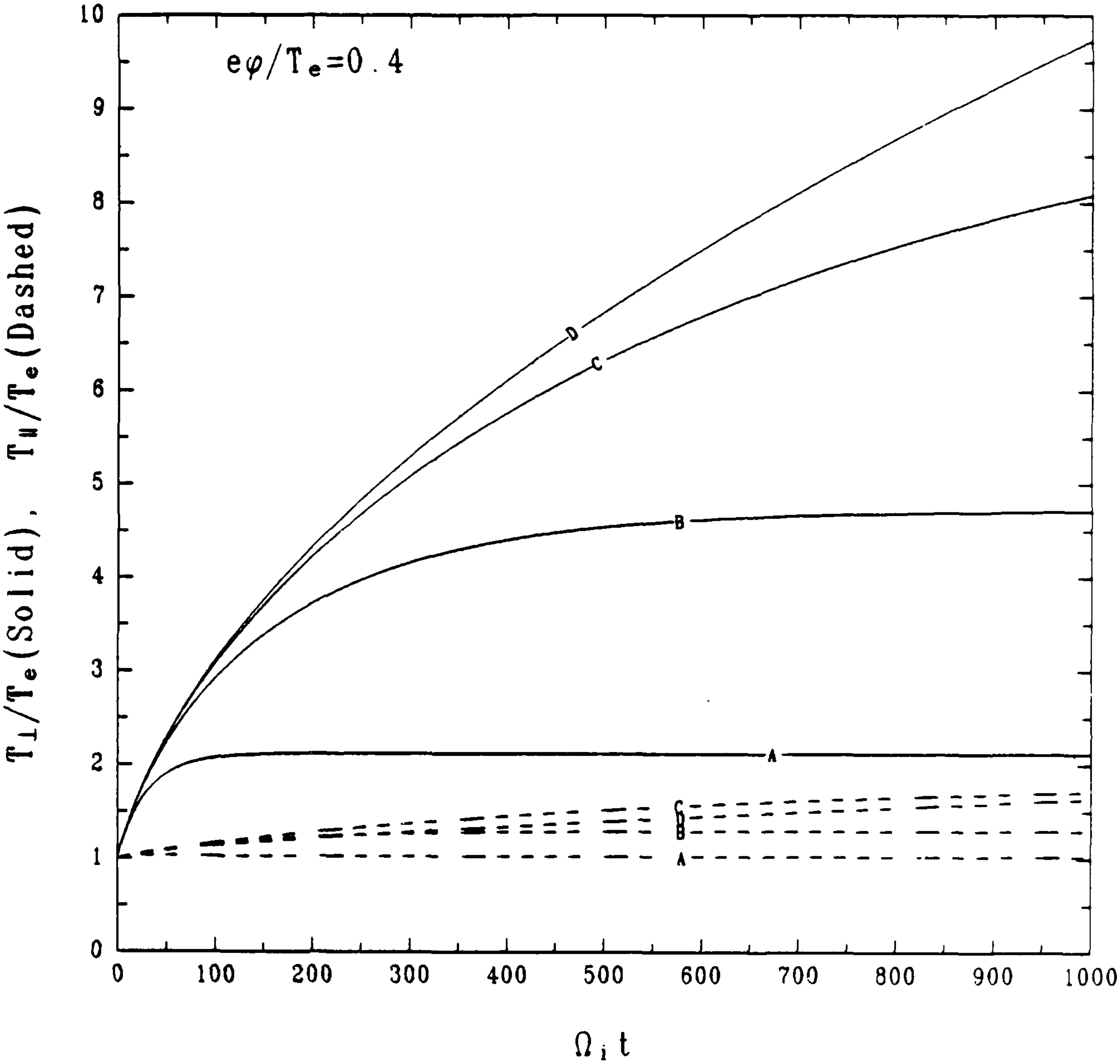

Fig. 2 Same as figure 1 except $e\phi/T_e = 0.4$.

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